Emittance preservation in a space-charge dominated ERL merger

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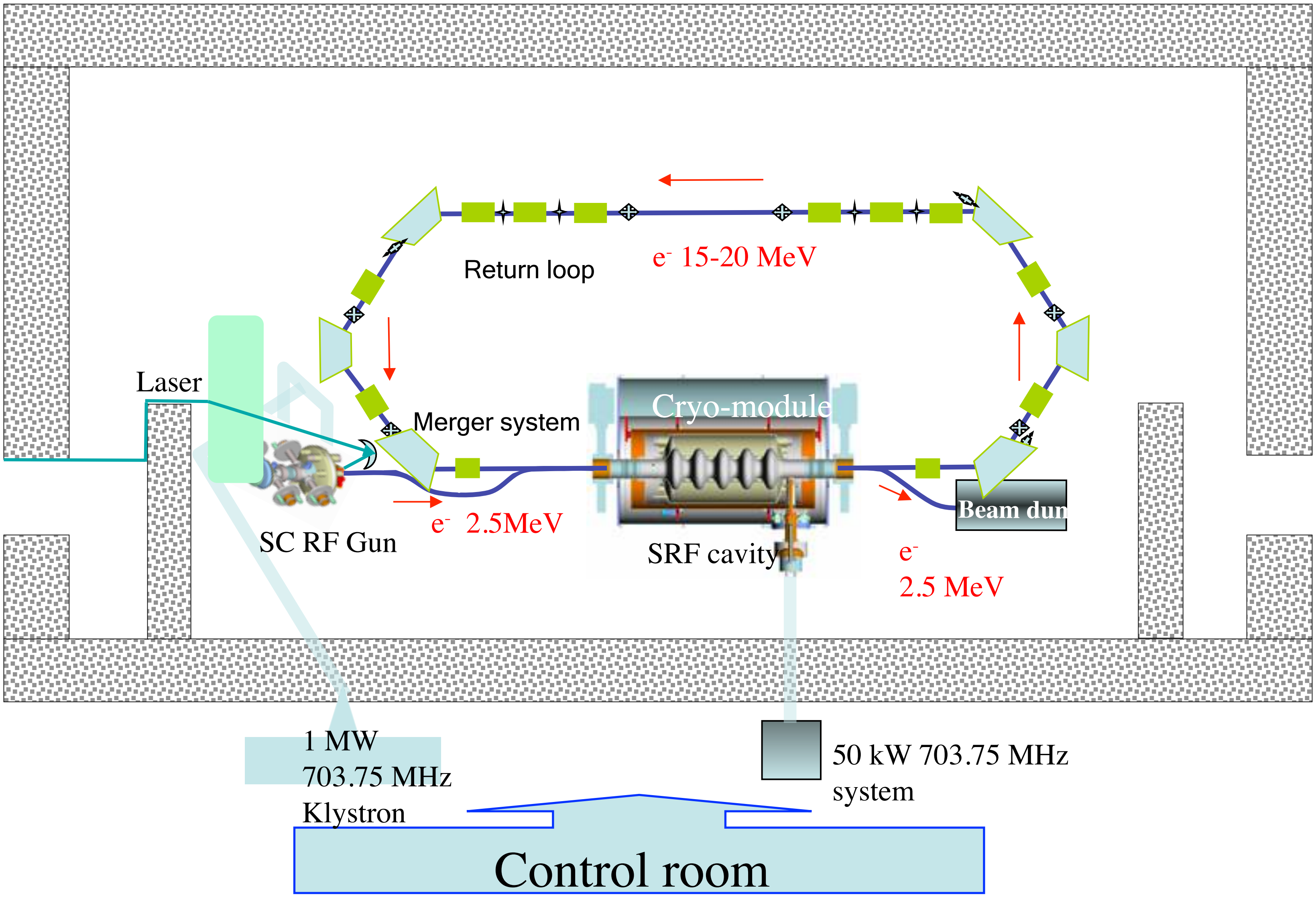
AP meeting September 5, 2008

Schematic Layout of the ERL

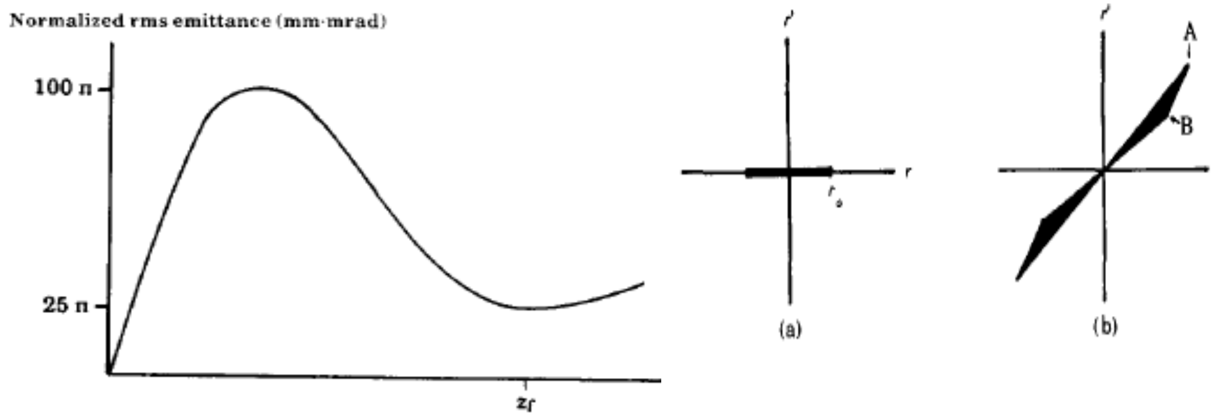


Some of ERL merger issues

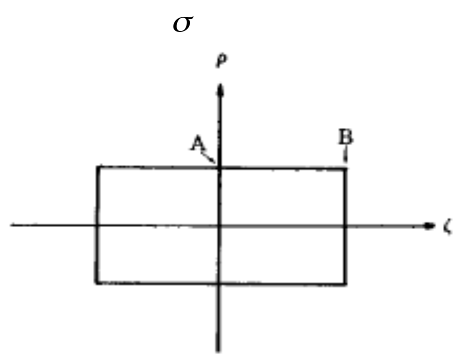
- Extraction (dumped) energy limitation (below 10 MeV)
- Power limitation:
  - 1 MW power supply is needed for high average current (0.5 A) and even for rather low 2 MeV injected beam
- Dipole magnets couple longitudinal and transvers motion

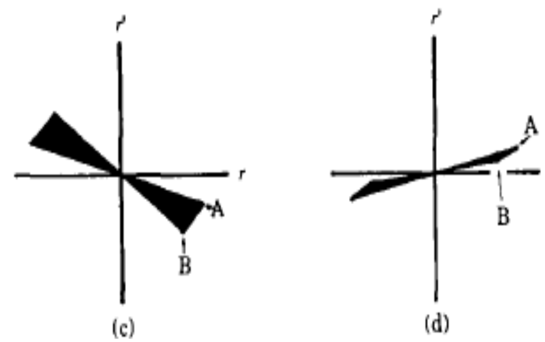
Emittance compensation

- After initial acceleration, space-charge field is mainly transverse (beam is long in rest frame).
- Transverse force dependent almost exclusively on local value of current density I/σ^2



$$\sigma_x''(\zeta,s)+K_r\cdot\sigma_x(\zeta,s)=\frac{r_e I(\zeta)}{2I_A(\beta\gamma)^3\sigma_x(\zeta,s)}+\frac{\varepsilon_{n,x}^2}{(\beta\gamma)^2\sigma_x^3(\zeta,s)}$$

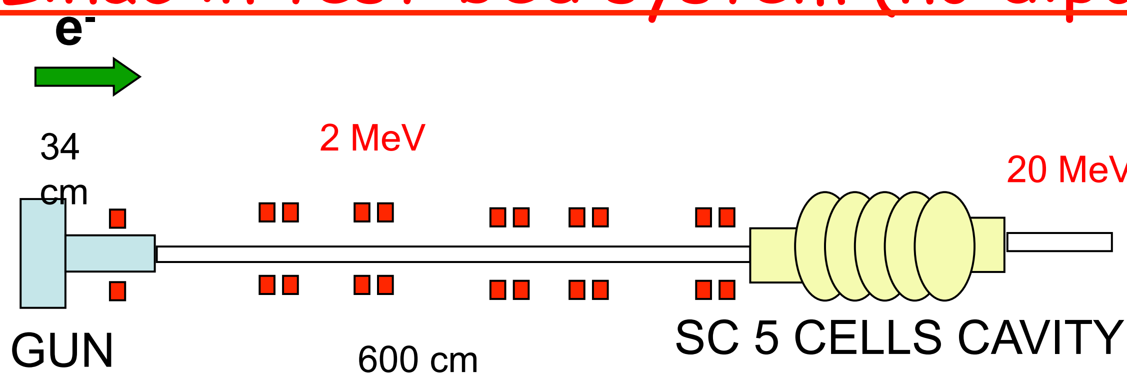




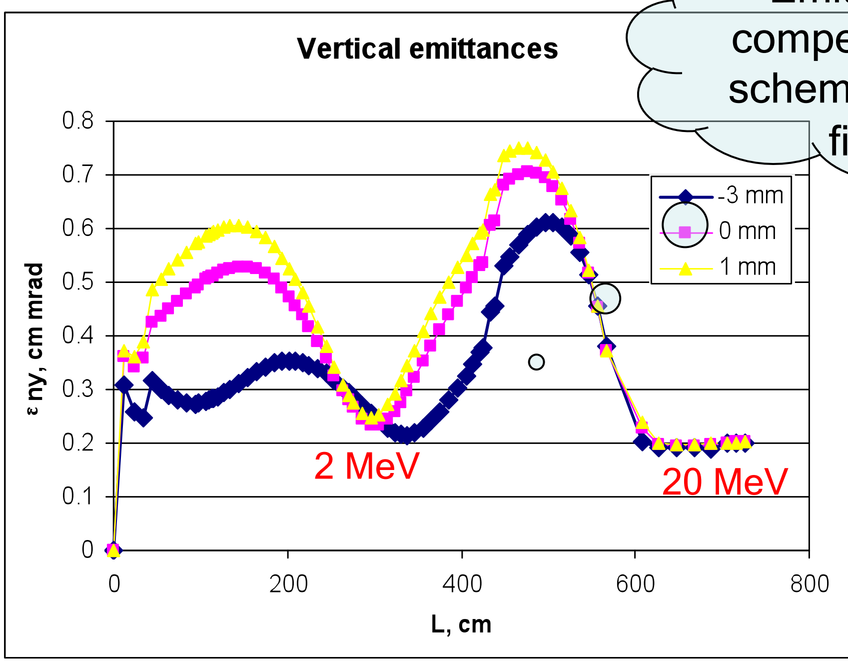
Simple model how the emittance compensation works [*]

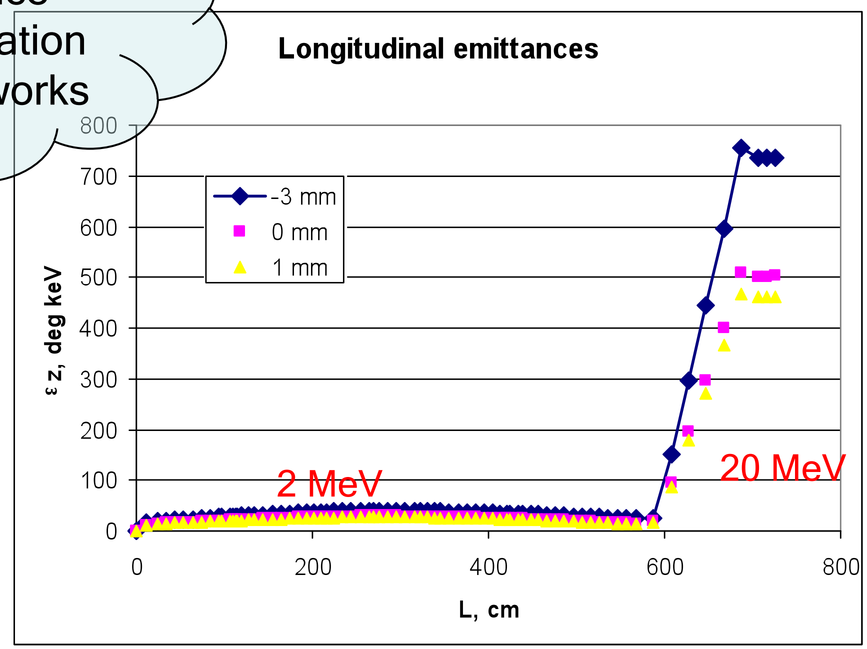
[*] B.E . Carlsten. New photoelectric injector design for the Los Alamos National Laboratory XUV FEL accelerator. NIMA 285 (1989) 313-319

Emittances evolution from cathod to the end of the Linac in test-bed system (no dipoles)

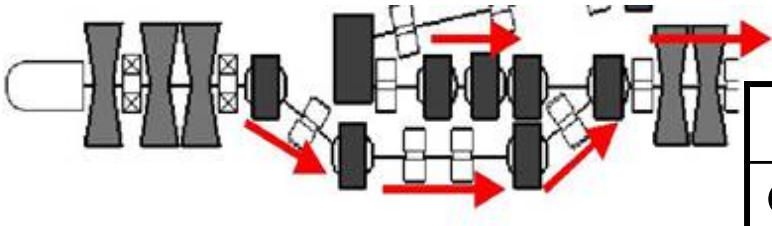


Emittance compensation scheme works fine

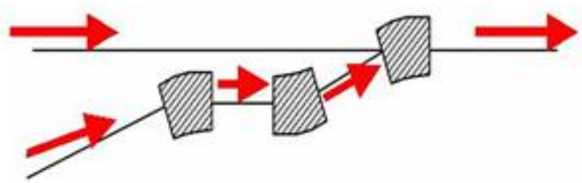




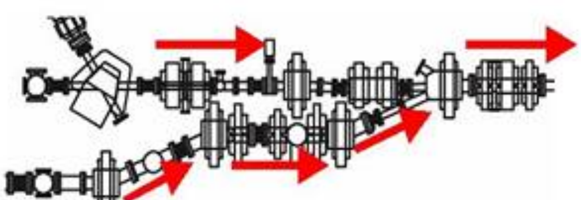
Mergers used in operational ERLs



Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia



Tomas Jefferson National Accelerator Facility (TJNAF) Newport News, VA, USA



Japan Atomic Energy Research Institute (JAERI), Tokai-mura, Ibaraki, Japan

Beam parameters

	BINP	TJNAF	JAERI
Gun type	Thermionic	Photocathode	Thermionic
Inj. energy	2 MeV	9.1 MeV	2.5 MeV
Max. energy	12 MeV	80-200 MeV	17 MeV
Q_bunch	1.5 nC	0.135 nC	0.5 nC
ΔT_bunch,	150 psec	2 psec	9.4 psec
Aver. current	25 mA	10 mA	5 mA
Merger type	Chicane, quad strong focusing	Three dipoles strong focusing	Dog-leg, quads strong focusing
Norm. emitt	30μ	10 μ	35/26 μ

Merger design for low emittance ERL

Existing ERLs provide normalize emittances 10-30 mm*mrad

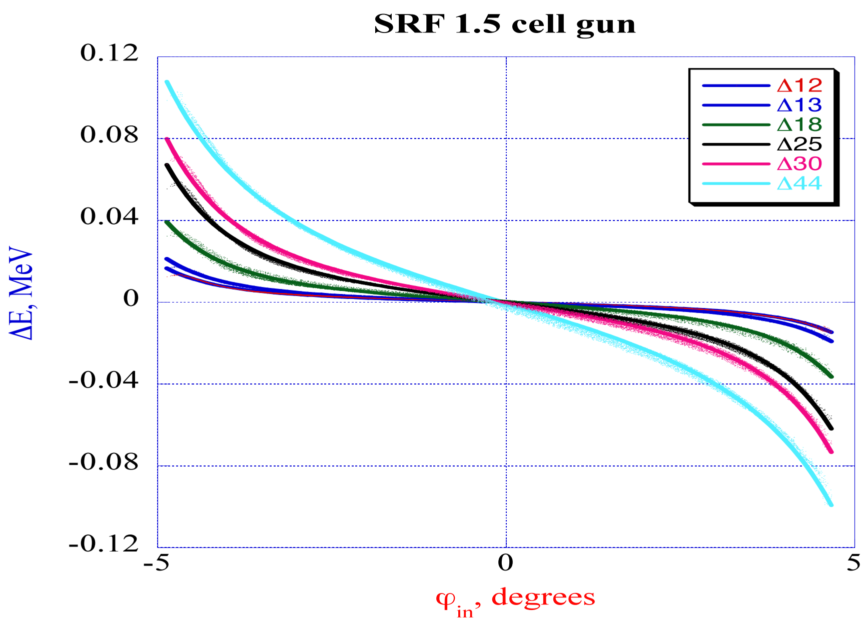
In linac photo-injectors 1mm*mrad was demonstrated

For the future ERL applications we are looking for system with normalized emittance < 1 mm* mrad

There are two effects which are important for design of a merger for space charge dominated e-beam:

1. **the space charge de-focusing must be taken into account** in the design of the achromatic merger. Defocusing caused by space charge can modify significantly the achromatic conditions;
2. **lattice of the merger must be designed with the use of only weakly focusing elements** with focal lengths larger or of the order of the merger length.

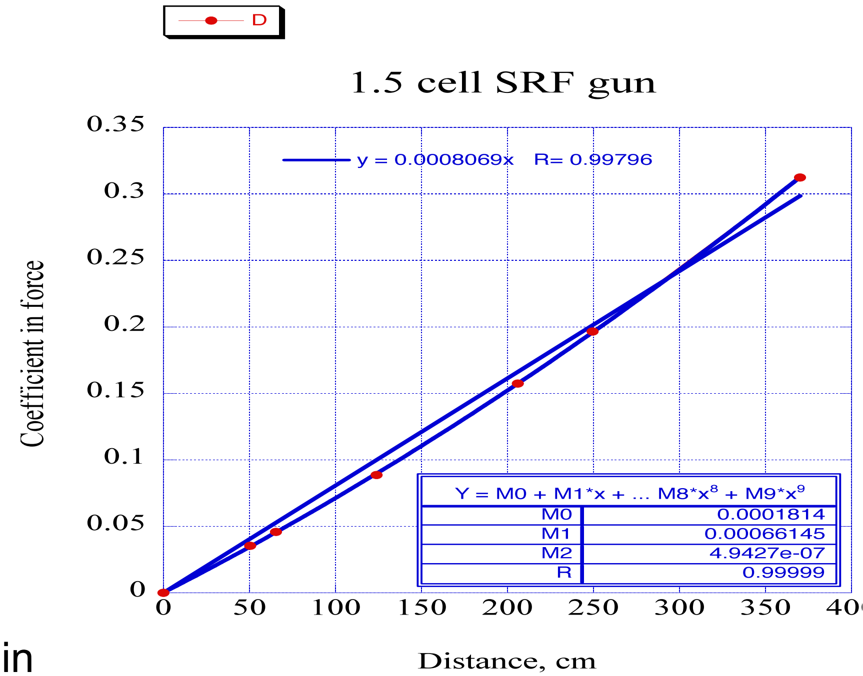
Energy changes study



Variation of electron energy, ΔE= E(s) - E(o), in a merger (caused by the space charge forces of 1 nC bunch) is a function of its position in the bunch. Different colors indicate different locations along the beam line.

Almost ideal fit to the field of evenly charged cylinder

$$\frac{dE}{ds} \cong eE(\zeta); \quad E(\zeta) = \frac{2Q}{r^2 \cdot 2l}\left(2\zeta - \sqrt{r^2 + (\zeta + l)^2} + \sqrt{r^2 + (\zeta - l)^2}\right)$$



Dependence of the energy gain on the azimuth *s.* Dots are the simulation results, the lines are linear and second-order polinomial fits.

$$\Delta E \cong \Delta E_i + f(\zeta_i) \cdot (s + \alpha \cdot s^2)$$

A typical s-dependent energy variation is very close to linear i.e. as in so-called frozen case.

Concept

Horizontal betatron oscillations around the ideal trajectory are described by homogeneous linear equation:

$$X = \begin{bmatrix} x \\ x' \end{bmatrix}; \ \frac{d}{ds} X \equiv X' = D(s) \cdot X; \ D(s) = \begin{bmatrix} 0 & 1 \\ -K_1(s) & 0 \end{bmatrix}$$

$$f\,ree\,oscillations \ X(s) = M(s_0 \mid s) \cdot X(s_0)$$

$$M' = D(s) \cdot M; \ \det M = 1; \ M(s_0) = I$$

For a particle with energy deviation δ (s)

$$E(s) = E_0(1 + \delta(s))$$

the equation of motion becomes inhomogeneous:

$$X' = D(s) \cdot X + \delta(s) \begin{bmatrix} 0 \\ K_0(s) \end{bmatrix}$$

where K0 – is the curvature of trajectory

With solution:

$$X(s) = M(s_0 \mid s) \cdot \left\{ X(s_0) + \int_{s_0}^{s} \delta(s_1) \cdot M(s_0 \mid s_1) \cdot \begin{bmatrix} 0 \\ K_0(s_1) \end{bmatrix} ds_1 \right\}$$

Concept (cont.)

There is specific solution for zero initial conditions R(s0)=0
generalized dispersion :

$$R(s) = \begin{bmatrix} \int_{s_0}^{s} \delta(s_1)\cdot m_{12}(s_1\,|\,s)\cdot K_0(s_1)ds_1 \\ \int_{s_0}^{s} \delta(s_1)\cdot m_{22}(s_1\,|\,s)\cdot K_0(s_1)ds_1 \end{bmatrix}$$

Rewriting for no energy change along transport line (δ=const) case.
Gives well-known transverse dispersion definition

$$\eta(s) = \int_{s_0}^{s} m_{12}(s_1\,|\,s)\cdot K_0(s_1)ds_1$$

$$\eta'(s) = \int_{s_0}^{s} m_{22}(s_1\,|\,s)\cdot K_0(s_1)ds_1$$

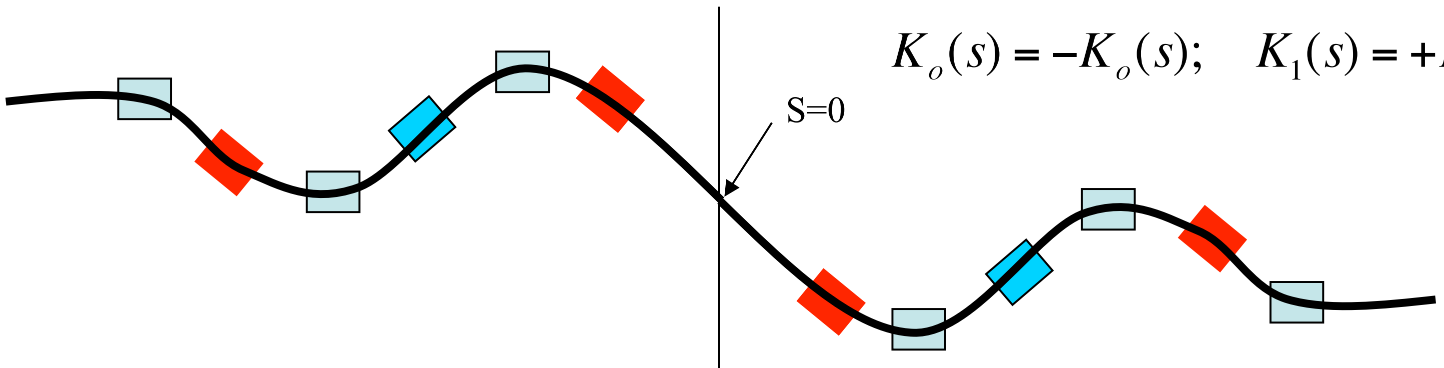
$$\delta_i(s) = \delta_{i0} + s\cdot g(\zeta_i) \Rightarrow \quad 4\text{ "}Achromat\text{" } conditions$$

$$\int_0^S K_o(s_1)\cdot m_{11}(s_1\,|\,s)ds_1 = 0; \qquad \int_0^S K_o(s_1)\cdot s_1\cdot m_{11}(s_1\,|\,s)ds_1 = 0;$$

$$\int_0^S K_o(s_1)\cdot m_{12}(s_1\,|\,s)ds_1 = 0; \qquad \int_0^S K_o(s_1)\cdot s_1\cdot m_{12}(s_1\,|\,s)ds_1 = 0;$$

System with bilateral symmetry (ZigZag):

Concept - cont.



$$K_o(s) = -K_o(s); \quad K_1(s) = +K_1(s)$$

$$M(-s) = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} M(s) \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \Rightarrow m_{11}(-s) = m_{11}(s); m_{12}(-s) = m_{12}(s)$$

$$K_o(-s)\cdot m_{11}(-s) = -K_o(s)\cdot m_{11}(s) \Rightarrow \int_{-L}^{L} K_o(s')\cdot m_{11}(s')ds' \equiv 0$$

$$K_o(-s)\cdot(-s)\cdot m_{12}(-s) = -K_o(s)\cdot(s)\cdot m_{12}(s) \Rightarrow \int_{-L}^{L} K_o(s')\cdot m_{12}(s')s'\cdot ds' \equiv 0$$

2 conditions are automatically satisfied

$$\int_0^L K_o(s')\cdot m_{12}(s')ds' = 0;$$

$$\int_0^L K_o(s')\cdot s\cdot m_{11}(s')ds' = 0;$$

2 conditions remain -> Two elements

Concept - cont.

No focusing

$m_{11} = 1; \quad m_{12} = s;$

$$\delta_i(s) = \delta_{i0} + s \cdot g(\zeta_i) \Rightarrow \quad 3 \text{ "}Achromat\text{" } conditions$$

$$\int_0^S K_o(s') \cdot ds' = \sum_k \theta_k = 0; \qquad \int_0^S K_o(s') \cdot s' \cdot ds' = \sum_k s_k \cdot \theta_k = 0;$$

$$\int_0^S K_o(s') \cdot s' \cdot ds' = \sum_k s_k \cdot \theta_k = 0; \quad \int_0^S K_o(s') \cdot s'^2 \cdot ds' = \sum_k s_k{}^2 \cdot \theta_k = 0;$$

In such system with bilateral symmetry (ZigZag)

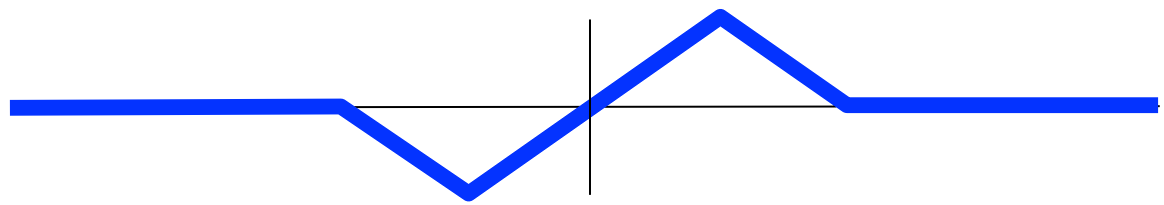
$$K_o(s) = -K_o(s); \quad K_1(s) = +K_1(s)$$

only one condition remains

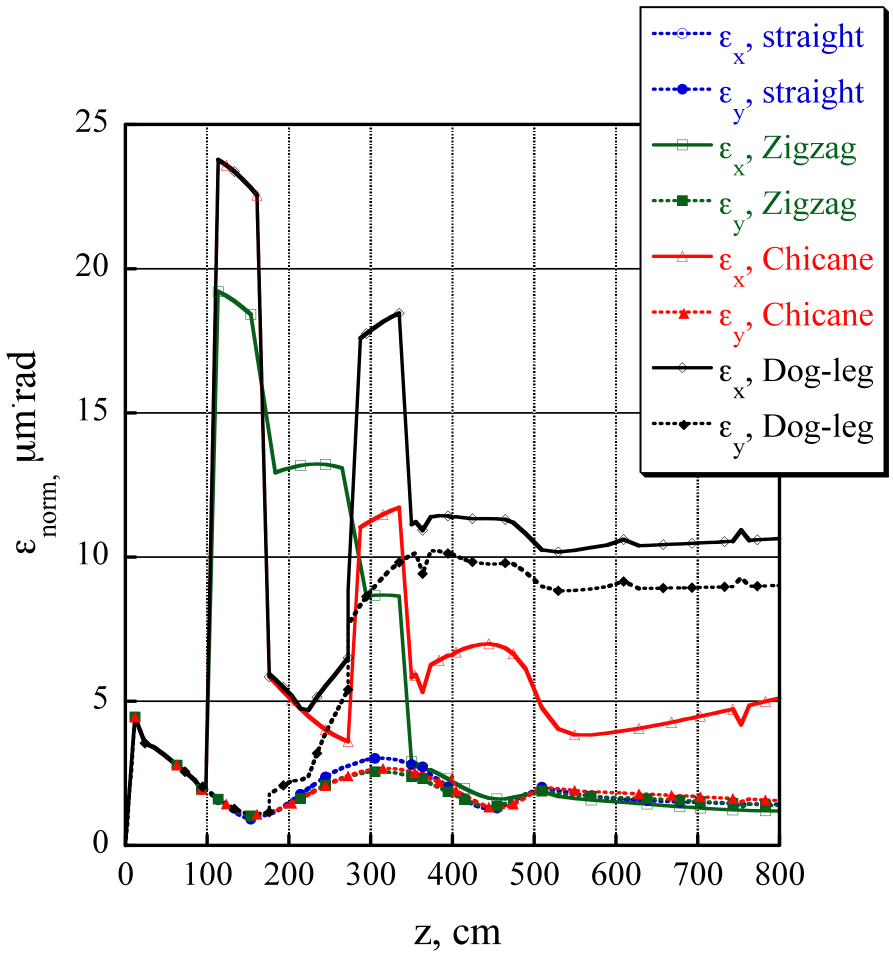
$$\sum_{k=1}^{K} s_k \cdot \theta_k = 0$$

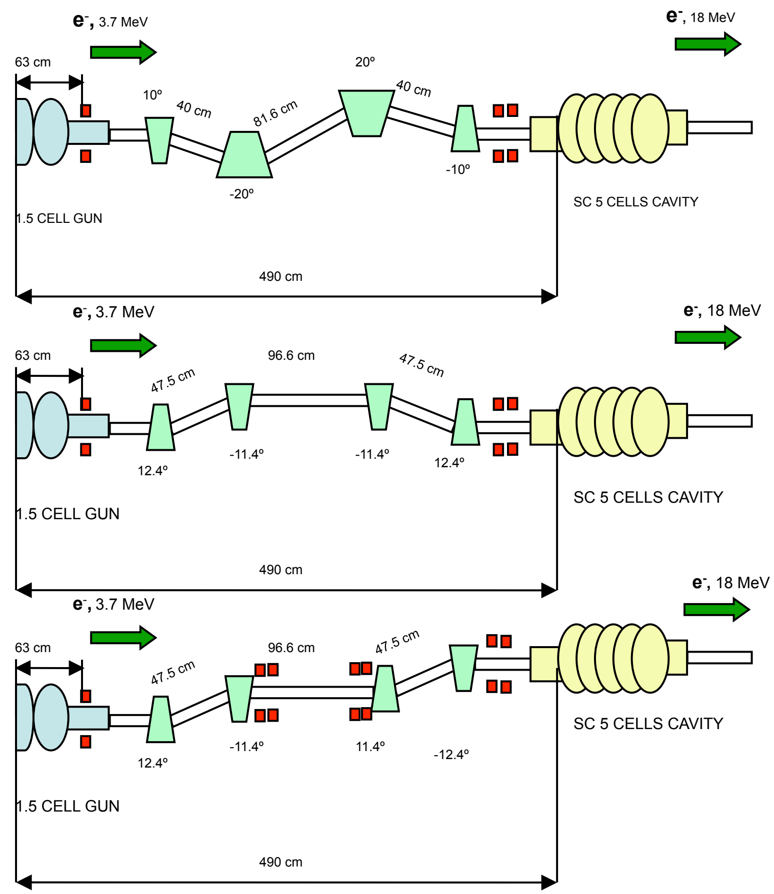
and it is trivial to satisfy in many ways with K=2.

Example: simplest ZigZag $s_2 = 2s_1; \quad \theta_1 = -2\theta_2$



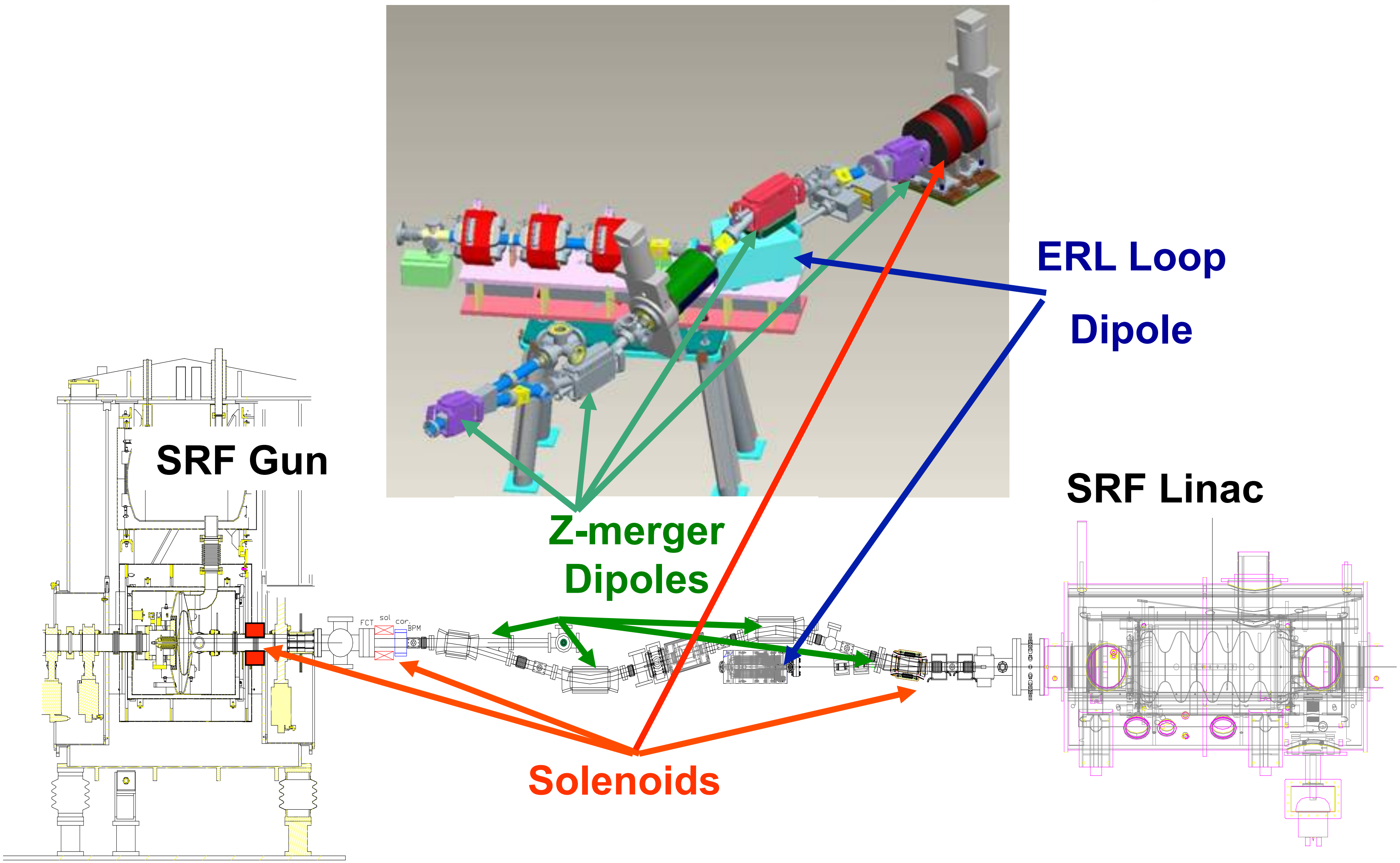
Compare of different merger systems



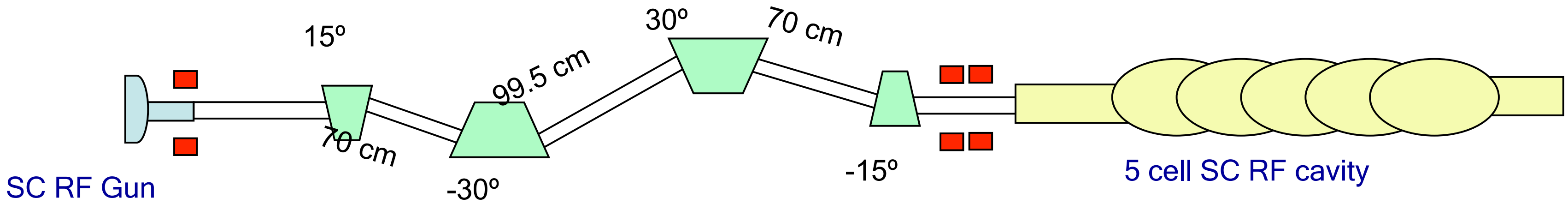


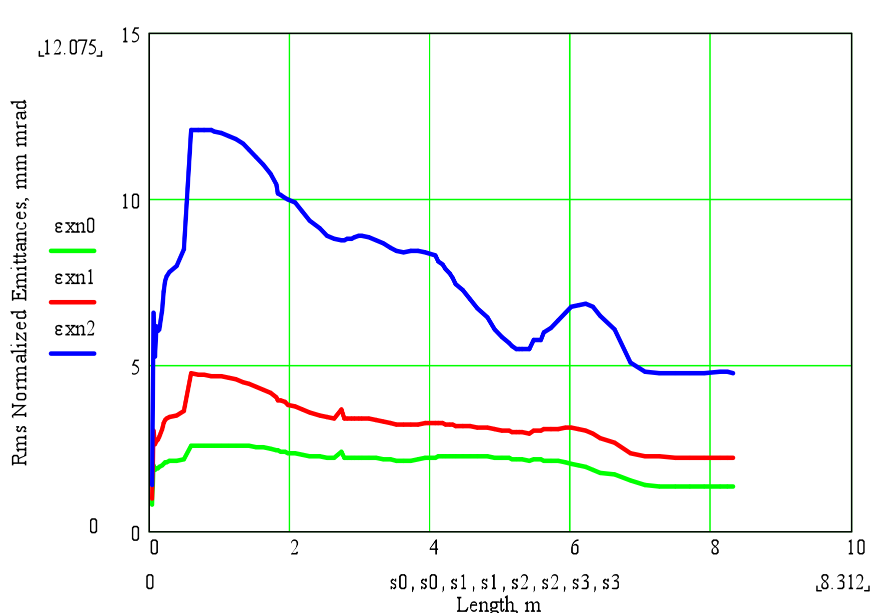
Evolution of horizontal and vertical normalized emittances in the four systems: the axially symmetric system, the Zigzag, the chicane and the Dog-leg. Result of PARMELA simulation: Q=1 nC, ber-can distribution, Gun_Energy=3.7 MeV, energy gain in Linac 15 MeV

BNL R&D ERL SRF Injector layout

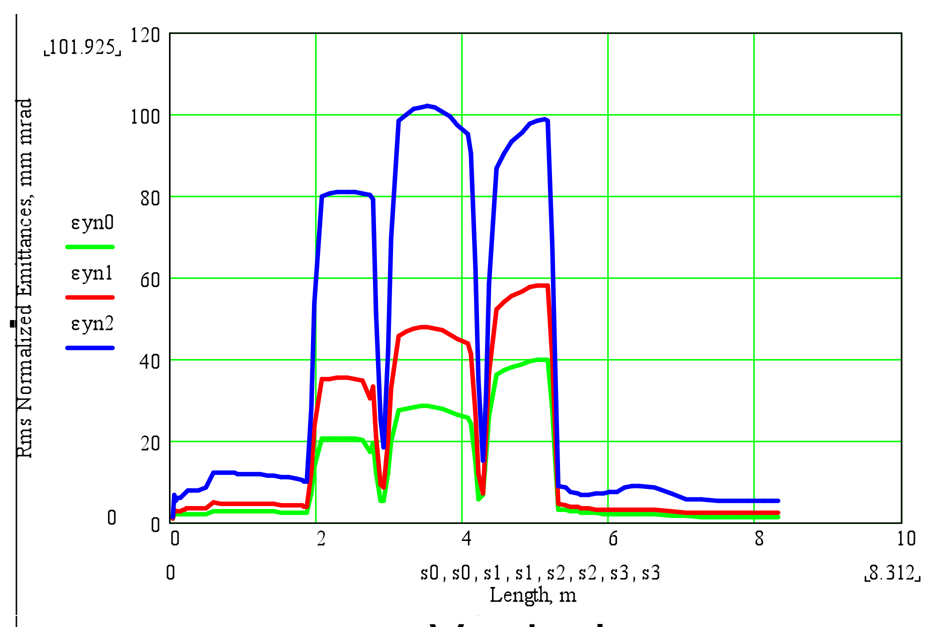


BNL ERL Injector: beam dynamics simulation results





Horizontal



Vertical

Evolution of normalized beam emittances in the BNL R&D ERL injector

Blue 5 nC	Red 1.4 nC	Green 0.7 nC
4.8/5.3 um	2.2/2.3 um	1.4/1.4um

R&D ERL beam parameters

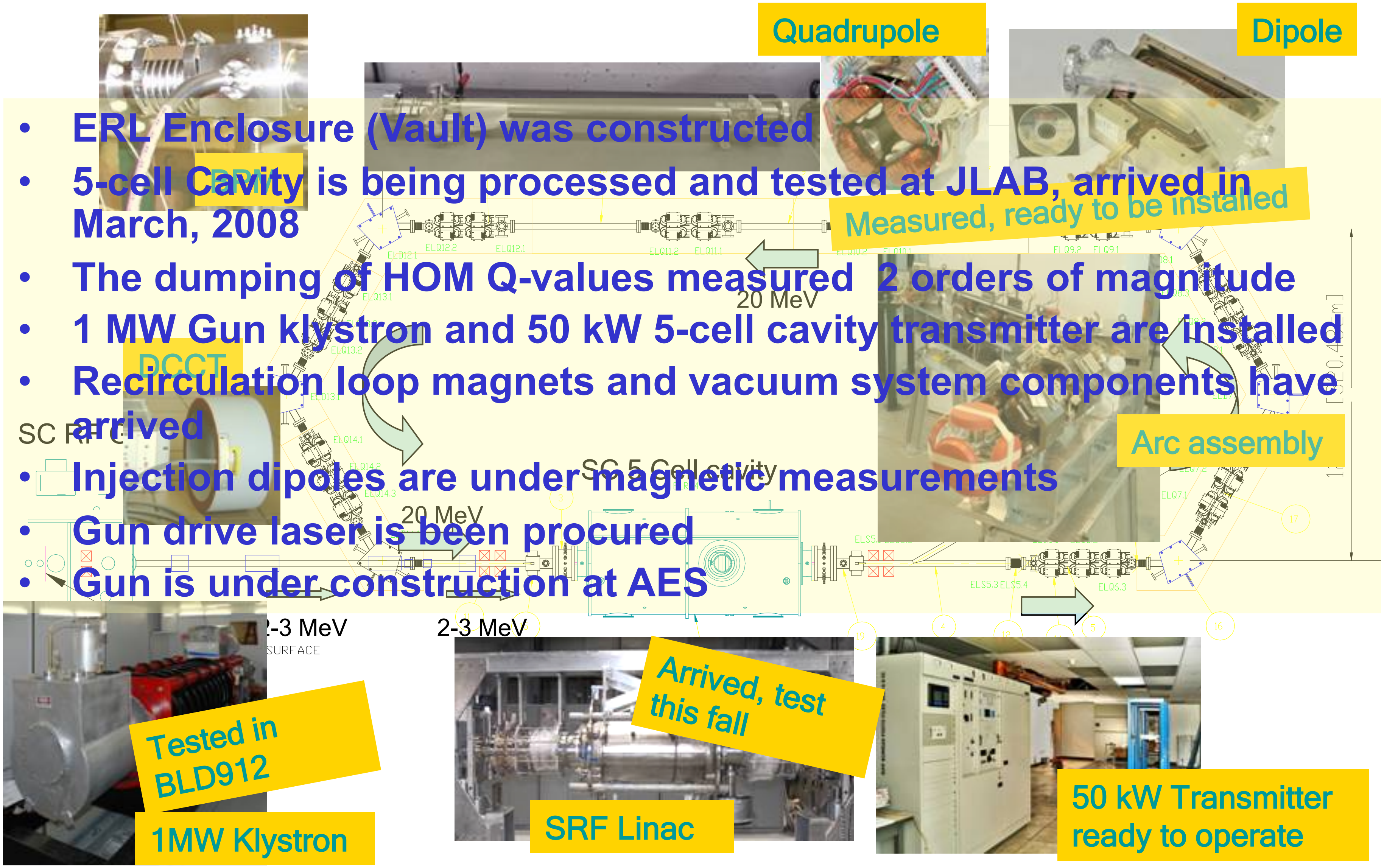
Parameter / Operation regime	High Current	High Current	High charge per bunch
Charge per bunch, nC	0.7	1.4	5
Numbers of passes	1	1	1
Energy maximum/injection, MeV	20/2.5	20/2.5	20/3.0
Bunch rep-rate, MHz	700	350	9.383
Average current, mA	500	500	50
Injected/ejected beam power, MW	1.0	1.0	0.15
R.m.s. Normalized emittances ex/ey, mm*mrad	1.4/1.4	2.2/2.3	4.8/5.3
R.m.s. Energy spread, $\delta E/E$	3.5×10^{-3}	5×10^{-3}	1×10^{-2}
R.m.s. Bunch length, ps	18	21	31

Conclusions

- ✓The concept of Zigzag merger works very well.
- ✓It's compatible with emittance compensation scheme.
- ✓The nonlinear effects starts play role for high charge per bunch mode
- ✓The experimental validity of the Zigzag merger and its performance in ERL will be tested in R&D ERL in building 912

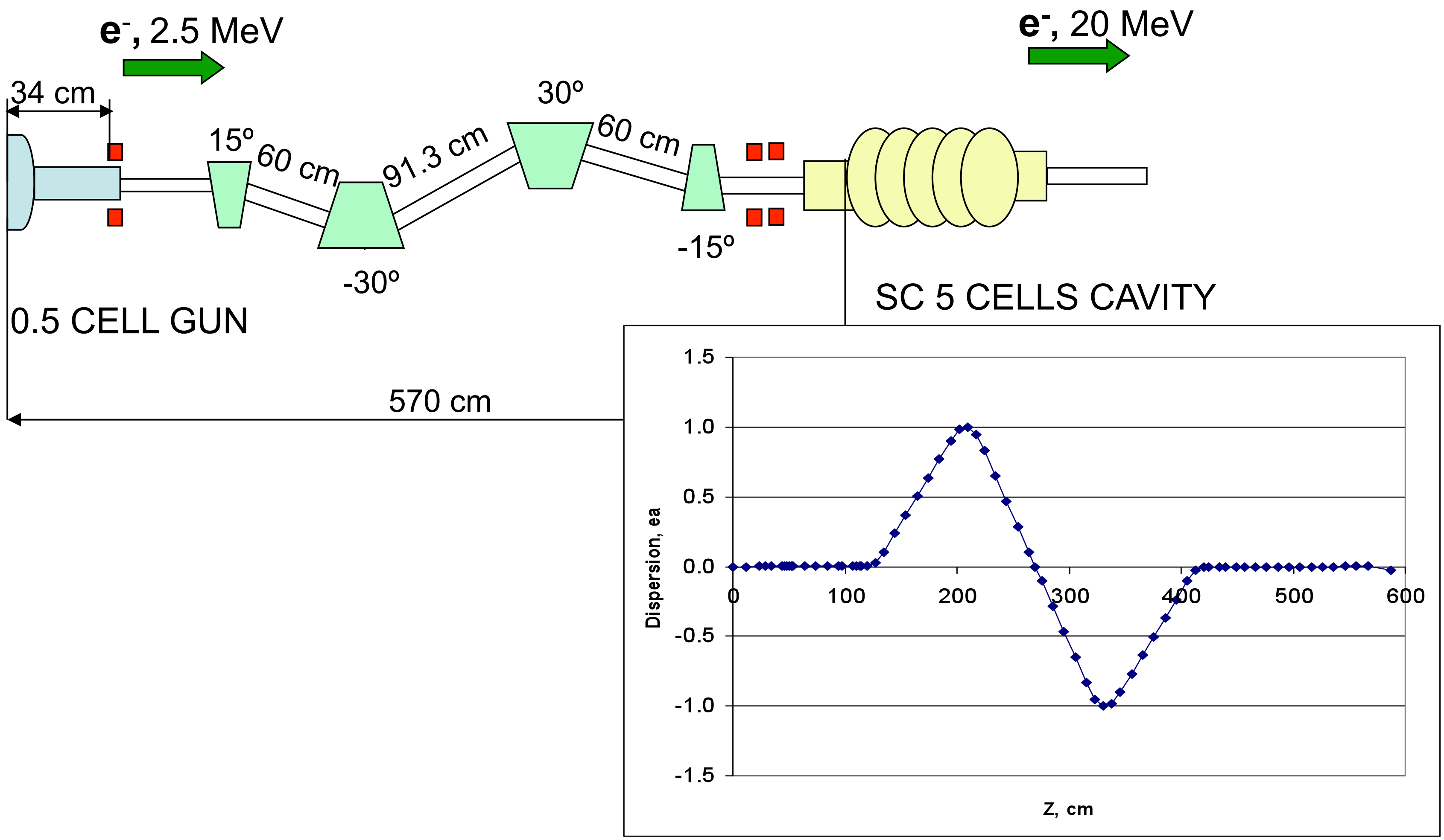
BNL R&D ERL: Status

- **ERL Enclosure (Vault) was constructed**
- **5-cell Cavity is being processed and tested at JLAB, arrived in March, 2008**
- **The dumping of HOM Q-values measured 2 orders of magnitude**
- **1 MW Gun klystron and 50 kW 5-cell cavity transmitter are installed**
- **Recirculation loop magnets and vacuum system components have arrived**
- **Injection dipoles are under magnetic measurements**
- **Gun drive laser is been procured**
- **Gun is under construction at AES**



- Back-up

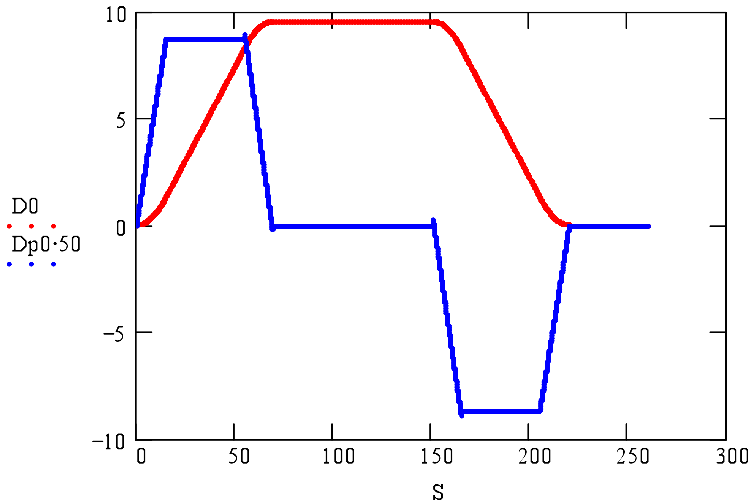
Zig-Zag



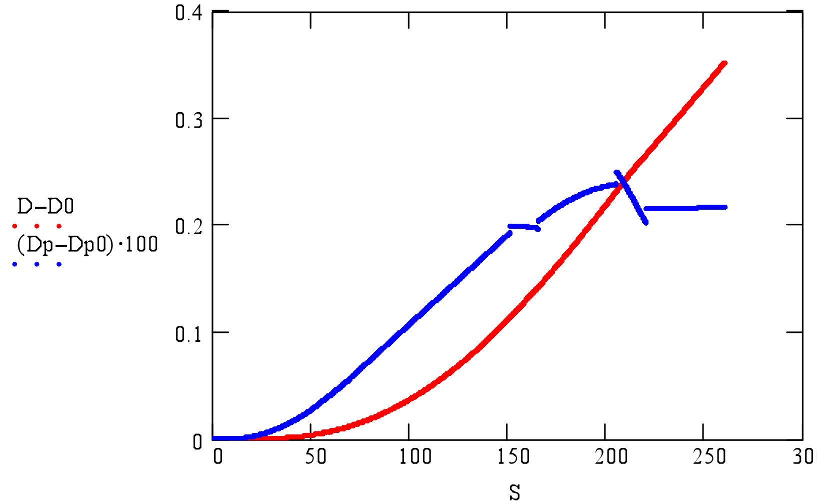
Dispersion in Zig-Zag system.

Merger: Achromatic Chicane (chevron dipoles)

Weak space charge Q=40pC



No space charge subtracted



Merger: Achromatic Zig-Zag (chevron dipoles)